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Laboratory and computing methods

METHODOLOGICAL INSTRUCTIONS FOR MERCURY POROSIMETRY OF CLASTIC SEDIMENTARY ROCKS

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Mercury porosimetry of clastic sedimentary rocks should be carried out on sample lumps of the following minimum dimensions: claystones to siltstones 7 mm, finegrained sandstones 8 mm, coarse-grained sandstones and conglomerates 10 mm and more (in dependence on the size of clastic grains). If the recommended sample sizes are not adhered to, rock artefacts are in fact analyzed. The pore volume distribution curves established on Carlo Erba and Micromeritics mercury porosimeters can be well unified on considering the respective differences in design.

1. INTRODUCTION

Cohesive clastic sedimentary rocks are a subject of study in a number of technological and scientific fields such as engineering geology, building construction, mining and hydrogeology. The base of these materials is formed by particles or minerals and rocks with sand or dust fraction sizes (clastics). The space between these particles is packed with a clayey substance. During the subsequent diagenetical changes the system is cemented together and reinforced with newly formed minerals (carbonates, quartz). The development of the rock is also associated with a simultaneous development of its internal pore structure [2].

The developed pore structure of rocks is most conveniently studied by the method of mercury porosimetry [3] which is capable of determining and distinguishing pores ranging from those visible with the naked eye to pores and cracks with sizes corresponding to a small multiple of molecular dimensions, and this all by a single measurement. Mercury porosimetry has become a standard method of pore analysis of current technical materials [4] including rock samples [5].

Routine porosimetric determinations of clastic sedimentary rocks tend to yield quite incomparable results in different laboratories. This is not only due to the considerable heterogeneity of the materials in question, but also to the fact that the specific characteristics of these natural materials are not always fully respected in the course of sample preparation. The present contribution has the aim to elucidate the primary methodical and instrumental effects which influence the determination of pore characteristics of clastic sedimentary rocks by the method of mercury porosimetry.

2. EXPERIMENTAL

2.1. Description and preparation of samples

The particle size of the material in question is the elementary problem in pore analysis of clastic sedimentary rocks. The sample should provide a representative description of the pore structure, as well as ensure a reproducible measuring result.

The porosimeters currently employed (Chapter 2.3) have dilatometers of cylindrical shape with a neck diameter of 10 to 25 mm. In an ideal case, the sample could be prepared by drilling a rock cylinder having the dimensions of the dilatometer, or cutting suitable plates (cubes) to suitable size. In actual practice, however, this way of sample preparation influences significantly the properties of the rock and frequently damages its original structure. Best results have therefore been obtained by preparing the sample by carefully breaking off lumps of suitable size. The piece placed in the dilatometer should be several times larger than the mean size of the clastic mineral. If the original configuration of the clastic grains and the cementing matter has not been retained, a rock artefact is actually analyzed.

The problems are particularly significant in the case of rocks composed of mineral particles of sand to nugget sizes, i.e. in that of sandstones and conglomerates. Samples of clastic sedimentary rocks from two black coal basins, differing in their degree and intensity of diagenesis, were therefore taken for the experiments (Table I). According to experience, Carboniferous rocks are suitable models for studying

Table I

Sample designation	Petrographic type	CMA	M_d [mm]	R [%]
1A	conglomerate	kaol. ill.	2	1.51
2A	coarse-grained sandstone	kaol. ill.	1.4*0.6	2.73
3A	medium-gr. sandstone	kaol. ill.	0.8*0.5	3.01
4A	fine-grained sandstone	kaol. ill.	0.5*0.2	1.86
5A	claystone	kaol.+ill.+IM	–	–
1B	conglomerate	ill. kaol.	2	1.28
2B	coarse-grained sandstone	ill. kaol.	0.8*0.3	1.43
3B	medium-gr. sandstone	ill. kaol.	0.5*0.2	1.83
4B	fine-grained sandstone	ill. kaol.	0.2*0.1	3.20
5B	claystone	ill. kaol. chl.	–	–

Sample designation: series A – Slaný Basin, Nýřany strata;
series B – Czechoslovak part of the Upper Silesian Basin;
the Karviná group of strata, saddle strata
CMA – association of clay minerals (kaol. – kaolinite, ill. – illite 10 Å, chl. – chlorite, IM – mixed structure of illite – montmorillonite)
R – difference in the values of ignition loss and CO_2 bound in carbonates

the pore structure of natural rocks as they allow a wide scale of factors typical for clastic sedimentary rocks to be demonstrated [2].

The following partial specimens were carefully prepared from the basic material (dia. 46 mm and 92 mm drill cores):
– a set of three cut platelets 10×14×15 mm in size
– crushed grain fraction 5.6–8.0 mm,
– crushed grain fraction 3.15–5.6 mm,
– crushed grain fraction 2.0–3.15 mm.

Before the measurement proper, the grains were X-rayed and all those showing internal defects were eliminated. Following the porosimetry, the specimens we-

re X-rayed again to establish possible damage to the internal structure. No such damage could be proved owing to the platelet thickness involved (5 mm).

2.2. Desiccation and evacuation of the samples

The samples were dried to a constant weight at 105° C and evacuated down to a residual pressure of less than 1 kPa [6].

The water bound freely in clastic rocks containing current associations of clay minerals (kaolinite and illite) is liberated up to 150°–170° C and the process does not involve any significant changes in volume [7]. However, in the case of rocks containing smectites or type illite-montmorillonite mixed structures in amounts exceeding 30 %, dehydration brings about considerable shrinkage which, in spite of the clay particles' cementing effect, may result in secondary porosity, revealed by an increase in the pore volume over the radius range exceeding 4 μm (Fig. 2b, 3 in ref. [8]).

At temperatures much higher than 100° C the coal matter, normally dispersed throughout the rock samples, becomes thermally degraded. Desiccation of the material at 105° C, followed by evacuation, can therefore be regarded as a considerate way of preparing the samples for porosimetric analysis.

2.3. Porosimetric analysis

The samples were analyzed at the same time on the 2000 Series Porosimeter using the Macropore 120 unit (Carlo Erba Strumentazione, Italy) and the Pore Sizer 9310 apparatus (Micromeritics Instruments Corporation, USA).

A study of the effect of the rate of pressure rise in the porosimeter on the results of analyses showed that in the case of rock samples, the total time of automatic high-pressure mercury intrusion should be at least 30–45 minutes. Only then the porosimetric curves obtained are smooth and do not show any defects due to non-uniform penetration of mercury into the sample. At higher rates of mercury intrusion, it is also impossible to determine the fine differences at the three pore volume differential distribution peaks whose intensity and position is of main interest in the interpretation of the porosimetric analyses of rocks [2].

The MICROSTRUCTURE program of the Porosimeter 2000 apparatus controls automatically the pressure increase at intrusion rates 2 to 3, so as to keep the decrease of mercury volume in the subsequent step at a suitably low level (the so-called intelligent step-wise mode).

On the Pore Sizer apparatus, 35 pairs of pressure and volume data were recorded over the 0.1 MPa–207 MPa interval with a dwelling period of 40 seconds at each step. On the average, 10 values of mercury penetration were obtained over the low-pressure range of 0.6 kPa–150 kPa.

The measuring results were converted in a standard way to the following conditions: wetting angle theta = 130 deg., surface tension of mercury = 0.485 N/m, the cylindrical pore shape model, the mercury compressibility correction of 1×10^{-11} Pa^{-1}.

3. RESULTS AND DISCUSSION

3.1. The effect of sample dimensions on the total pore volume established by mercury porosimetry

As indicated by the results plotted in Figs. 1 and 2, the shape of the dependence of total pore volume (determined by mercury porosimetry) on sample size is characteristic of the given petrographic type of the rock.

Conglomerates from both coal basins exhibit high values of total pore volume in the case of cut platelets, because the macrostructure of the bulk rock is comparatively well preserved by this way of sample preparation. Breaking up and crushing bring about an increase in the content of clastic particles and the total pore volume determined in the samples decreases (Fig. 1).

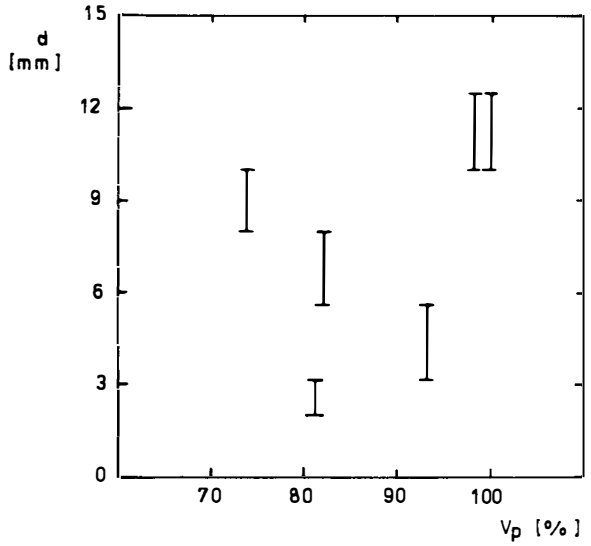

Fig. 1. The effect of sample size on the total volume of pores determined by mercury porosimetry. Conglomerate 1B, V_p (100 %) = 24.0 mm^3/g, Pore Sizer 9310.

There is a different trend in the case of sandstones and claystones (Fig. 2). Higher total pore volume values are shown by smaller samples obtained by breaking up the rock. The higher total pore volume is due to a higher representation of agglomerates of clastic grains, joined by the base material, and to an increase in interparticle porosity in the dilatometer [9].

The dimensions given in Fig. A1 in the Annex can be recommended as the minimum sample lump sizes to be employed in porosimetric analyses of clastic sedimentary rocks.

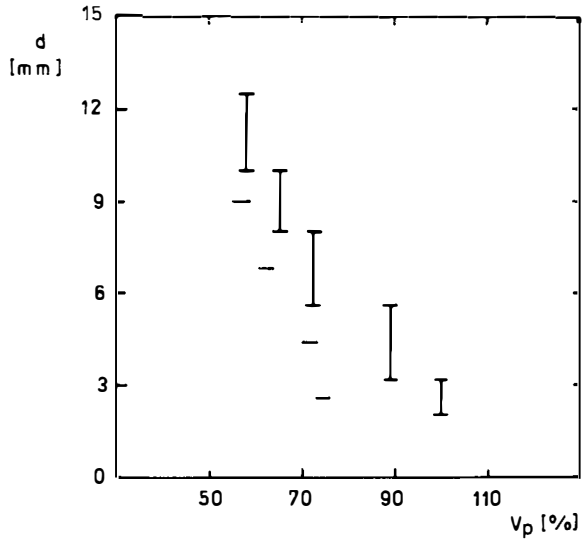

Fig. 2. The effect of sample size on the total volume of pores determined by mercury porosimetry. Medium-grained sandstone 3A, V_p (100 %) = 35.5 mm^3/g,
⊢⊣ – Pore Sizer 9310, —— – Porosimeter 2000 a Macropore 120.

3.2. The effect of sample size on pore volume distribution

The breaking up of rock specimens affects not only the total pore volume value, but also the pore volume distribution.

As described in detail in ref. [2], the pore distribution curves of Carboniferous sedimentary rocks can be divided into three size categories, and the pore volumes in the categories, related to the total pore volume in the sample, can be expressed by means of percentual parameters *A, B, C* or α, β, γ. This expressing allows the pore size distribution curve of each sample to be characterized by a single point in a triangular diagram whose apexes correspond to 100 % representation of the pore volume in the individual size categories (Figs. 3 and 4).

The projections of pore distribution curves of samples studied within the framework of the present work indicate the possible dispersion of results due to different sample sizes:

With claystones to sandstones, the decreasing sample size brings about a gradual increase in the content of category *A* or α pores. This fact indicates beginning formation of an artefact structure with a growing proportion of large-size pores (Fig. 4).

In the case of conglomerates, the shift of projection points in the triangular diagrams shows the opposite trend. With these samples, decreasing sample size results in a gradually prevailing influence of the pore system of the clastic grains with adhering minerals of the basic matrix (Fig. 3).

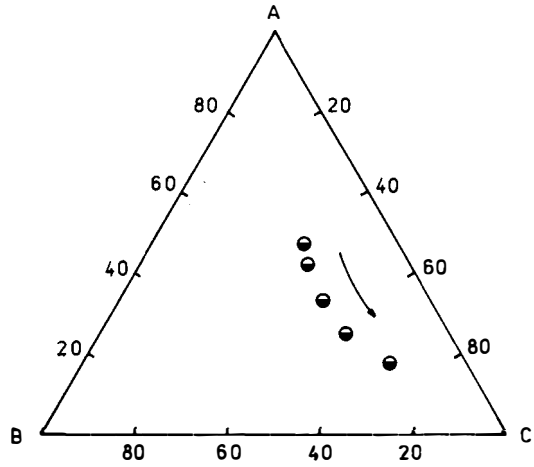

Fig. 3. Diagram of pore volume distribution in A, B, C categories. Conglomerate 1B. Pore Sizer 9310. A – share of pores with $r > 0.5$ μm in the total pore volume V_p (%), B – share of pores with $r = 0.05–0.5$ μm in the total pore volume V_p (%), C – share of pores with $r < 0.05$ μm in the total pore volume V_p (%), The arrow indicates the direction of decrease of the sample size.

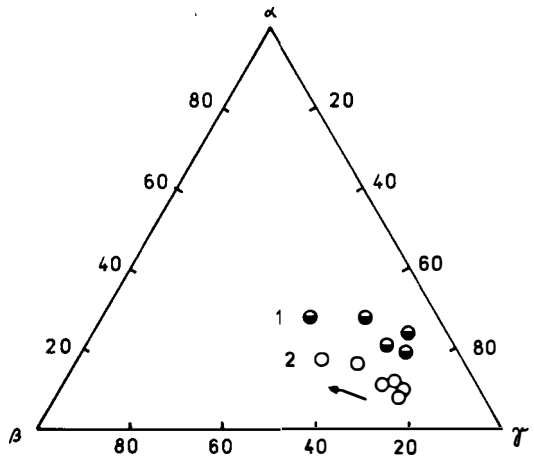

Fig. 4. Diagram of pore size distribution in categories α, β, γ. Medium-grained sandstone 3A. α – share of pores with $r > 4$ μm in the total pore volume V_p (%), β – share of pores with $r = 0.1–4$ μm in the total pore volume V_p (%), γ – share of pores with $r < 0.1$ μm in the total pore volume V_p (%), The arrow indicates the direction of decrease of the sample size. 1 – Pore Sizer 9310, 2 – Porosimeter 2000 with the Macropore 120 unit.

3.3. Comparability of the results of measurements on two types of porosimeters

The difference in the results of measurements repeated four to five times on both types of porosimeters was better than 5 % for total pore volume.

Analyses of rock samples carried out in parallel on the Porosimeter 2000 Series with the Macropore 120 unit and the Pore Sizer 9310 apparatus indicate that the total pore volumes for most of the samples were on the average smaller by 10 % with the former apparatus (Fig. 2).

This difference, which manifests itself by pore distribution primarily at the expense of pores with diameters exceeding 4 μm (Fig. 4), is due to the different designs of the low-pressure units of the porosimeters. During routine analyses on the Macropore 120 device, the vertical elevation of the mercury column in the capillary of the dilatometer allows only pores with equivalent radii smaller than about 50 μm to be determined. On the other hand, the horizontal mercury supply technique employed in Pore Sizer 9310 permits the analysis to be started with pore radii from about 100 μm upwards.

The Carboniferous rocks are materials with a relatively low porosity and an almost uniform pore distribution curve. The share of volume of pores with radii ranging from 50 μm to 100 μm is relatively significant in these samples (Figs. 5 and 6), and the Pore Sizer 9310 apparatus also appears to be more sensitive with respect to the sample size (Fig. 2). If the results of analyses carried out by

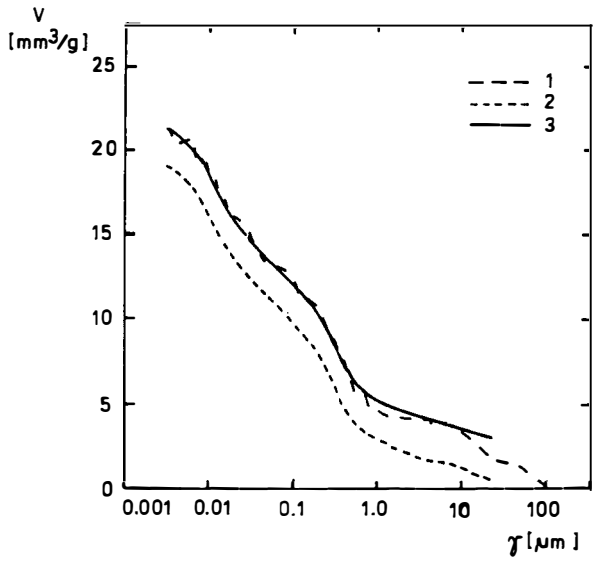

Fig. 5. Cumulative pore distribution curve. Medium-grained sandstone 3B. 1 – Pore Sizer 9310, 2 – Porosimeter 2000 with the Macropore 120 unit, 3 – Curve (2) transposed to the level of curve (1), vertical shift by 2.3 mm^3/g.

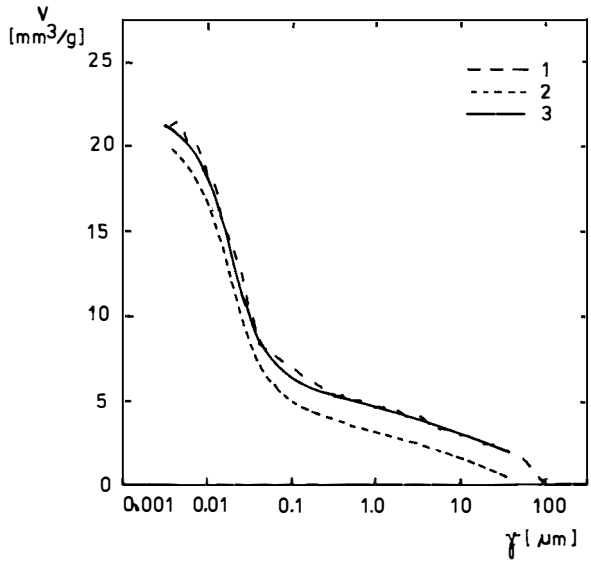

Fig. 6. Cumulative pore distribution curve. Medium-grained sandstone 3A. 1 – Pore Sizer 9310, 2 – Porosimeter 2000 with the Macropore 120 unit, 3 – Curve (2) transposed to the level of curve (1), vertical shift by 1.4 mm^3/g.

the two types of instruments are to be interpreted at the same time, the results obtained from Pore Sizer 9310 have to be corrected for the volume of pores with radii exceeding 50 μm.

4. CONCLUSIONS

Because of a low porosity and a wide pore size distribution in clastic sedimentary rocks, the porometric analysis of their samples by mercury porosimetry is very sensitive to the measuring conditions employed. In joint evaluations of porosity measurements carried out in various laboratories one has to take into account a number of informations on the actual conditions of the respective measurements. Comparisons should be made only of samples analyzed with the use of a unified optimized procedure. A proposal of a method of sample taking, preparation and the porosimetric analysis proper of clastic seimentary rocks is presented in the Annex.

ANNEX

Proposal of a standardized method for porosimetric analysis of clastic sedimentary rocks

1. Sampling

Samples of rocks for porosimetric analysis should be supplied in lumps approximately 10×10×15 cm in size. Drill core lumps can also be used. The sample for analysis should not have a dimension smaller than 2 cm. Maximum attention

should be paid to the representativeness of the sample taken (sediment texture and structure).

The sample taken should be placed in a polythene bag and well sealed. Samples in such packaging should be delivered to the laboratory.

2. Sample preparation for porosimetric analysis

Before the analysis proper, break the rock lumps carefully into pieces with sizes smaller than the opening of the mercury dilatometer (usually 11–24 mm). The minimum size of the rock pieces to be used in porosimetric analysis should depend on the petrographic type of the rock. Fig. A1 shows the recommended minimum dimensions of specimens for the basic types of clastic sedimentary rocks.

The specimens intended for porosimetric analysis should be dried at 105° C to a constant weight. The weight of the sample should allow the sensitivity of the apparatus to be utilized in an optimum way. In the low-pressure section of the porosimeter, the material should be evacuated until the pressure falls permanently below 1 kPa.

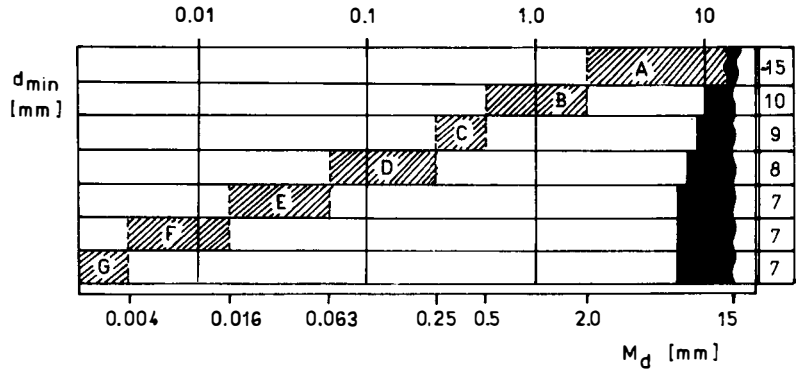

Fig. A1. Minimum sizes of samples for mercury porosimetry of clastic sedimentary rocks. d – recommended minimum sample size, M_d – mean size of clastic grains, A – conglomerates, B – coarse-grained sandstone, C – medium-grained sandstone, D – fine-grained sandstone, E – coarse-grained siltstone, F – fine grained siltstone, G – claystones.

3. Porosimetric analysis and evaluation of the result

The porosimetric analysis should be carried out strictly according to the instructions for use of the respective porosimeter.

The rate of increasing the pressure in the high-pressure unit should be programmed in such a way that the intrusion stage of the high-pressure analysis proceed uniformly for at least 30 minutes.

The basic output of the measurement is given by pore size distribution curves in both cumulative and differential form, and a set of the following porosity characteristics determined by mercury porosimetry: total volume of pores, specific surface area, apparent density, effective porosity, and possibly also the A, B, C and α, β, γ parameters (see Figs. 3 and 4).

The type of the porosimeter employed and the range of the maximum and minimum pressure attained during the measurement, the pore shape model, the value of mercury surface tension and that of the contact angle employed should always be specified together with the results obtained. If the precise value of the contact angle of mercury on the sample is unknown, use should be made of the value $\Theta = 141.3°$, which is close to the mean contact angles of mercury with respect to quartz, kaolinite and illite [10]. It is advisable to correct the results in a standard way for the compressibility of mercury (blank experiment).

4. Associated analytical and petrographical analyses

In order to interpret correctly the results of porosimetric analyses, additional determinations should be made on the rock sample:

a) petrographic description of the rock (analysis of the composition and grain sizes of its minerals, identification of minerals in the matrix and the cement, determination of the type and content of the dispersed coal matter),

b) determination of the ignition loss (ČSN 72 0103),

c) determination of free water content (ČSN 72 0104),

d) determination of carbon dioxide bound in carbonates (ČSN 72 0121)[1]

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[1] The difference between items b) and c) is proportional to the content of coal and clay substances taking part in blocking the porous structure of the rocks [2].

METODIKA RTUŤOVÉ PÓROMETRIE KLASTICKÝCH SEDIMENTÁRNÍCH HORNIN

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K získání správných výsledků při rtuťové pórometrii sedimentárních hornin tvořených písčitými a prachovitými zrny s jemnou výplní částicemi jílů a tmelů je zapotřebí, aby vzorky použité k měření měly zachovanou konfiguraci zrn a mezerní hmoty v objemu horniny. Pro studium vlivu velikosti vzorku na pórové charakteristiky byly použity sedimentární horniny karbonského stáří. Na těchto materiálech bylo možno reprezentativně ukázat, jak minerální složení a textura horniny může ovlivnit výsledky pórometrických měření (typické příklady jsou uvedeny na obr. 1–4).

Součástí práce je návrh metodického postupu pro odběr, přípravu vzorků a vyhodnocení výsledků pórometrických měření. Doporučené minimální velikosti vzorku pro hlavní petrografické typy klastických hornin jsou uvedeny na obr. A1. Metodika je vhodná pro všechny druhy klastických sedimentů s různým stupněm diageneze a stáří.

Reprodukovatelnost stanovení pórových charakteristik sedimentárních hornin byla sledována na dvou běžně rozšířených pórometrech – Porosimeter 2000 s jednotkou Macropore 120 (Carlo Erba, Itálie) a Pore Sizer 9310 (Micromeritics, USA). Je ukázáno, že odlišný způsob plnění dilatometrů rtutí u obou přístrojů může při rutinních analýzách způsobit několikanásobně vyšší rozdíl výsledků než je rozptyl opakovaného měření.

Po uvážení tohoto vlivu je však možno distribuční křivky pórů horninových vzorků stanovené na obou typech přístrojů velmi dobře sjednotit pouhou objemovou translací (obr. 5, 6).

Obr. 1. Vliv velikosti vzorku d na celkový objem pórů V_p stanovený rtuťovou pórometrií. Konglomerát 1B, V_p (100 %) = 24,0 mm^3/g, Pore Sizer 9310.

Obr. 2. Vliv velikosti vzorku d na celkový objem pórů V_p stanovený rtuťovou pórometrií. Střednozrnný pískovec 3A, V_p (100 %) = 35,5 mm^3/g, ├─┤ – Pore Sizer 9310, —— – Porosimeter 2000 a Macropore 120.

Obr. 3 Diagram distribuce objemu pórů v kategoriích A–B–C. Konglomerát 1B. Pore Sizer 9310. A – podíl objemu pórů o poloměrech $r > 0{,}5$ μm na celkovém objemu pórů vzorku V_p (%), B – podíl objemu pórů o poloměrech $r = 0{,}05$–$0{,}5$ μm na celkovém objemu pórů vzorku V_p (%), C – podíl objemu pórů o poloměrech $r < 0{,}05$ μm na celkovém objemu pórů vzorku V_p (%), Šipka znázorňuje směr poklesu velikosti úlomku.

Obr. 4. Diagram distribuce objemu pórů v kategoriích α–β–γ. Střednozrnný pískovec 3A. α – podíl objemu pórů o poloměrech $r > 4$ μm na celkovém objemu pórů vzorku V_p (%), β – podíl objemu pórů o poloměrech $r = 0{,}1$–4 μm na celkovém objemu pórů vzorku V_p (%), γ – podíl objemu pórů o poloměrech $r < 0{,}1$ μm na celkovém objemu pórů vzorku V_p (%). Šipka znázorňuje směr poklesu velikosti úlomku. 1 – Pore Sizer 9310, 2 – Porosimeter 2000 s jednotkou Macropore 120.

Obr. 5. Kumulační distribuční křivka pórů. Střednozrnný pískovec 3B. 1 – Pore Sizer 9310. 2 – Porosimeter 2000 s jednotkou Macropore 120. 3 – křivka (2) transponovaná na úroveň křivky (1), vertikální posun o 2,3 mm^3/g.

Obr. 6. Kumulační distribuční křivka pórů. Střednozrnný pískovec 3A. 1 – Pore Sizer 9310. 2 – Porosimeter 2000 s jednotkou Macropore 120. 3 – křivka (2) transponovaná na úroveň křivky (1), vertikální posun o 1,4 mm^3/g.

Obr. A1 Minimální rozměry vzorků pro rtuťovou pórometrii klastických sedimentárních hornin. d – doporučená minimální velikost vzorku, M_d – střední velikost klastických zrn, A – konglomeráty, B – hrubozrnný pískovec, C – střednozrnný pískovec, D – jemnozrnný pískovec, E – hrubozrnný prachovec, F – jemnozrnný prachovec, G – jílovce.

МЕТОДИКА РТУТНОЙ ПОРОМЕТРИИ КЛАСТИЧЕСКИХ ОСАДОЧНЫХ ПОРОД

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Для получения точных результатов с помощью ртутной порометрии осадочных пород, образующихся песчаными и мелкоземными зернами с тонким заполнением частицами илов и цемента показывается необходимым, чтобы у проб, предназначенных для измерения сохранялась конфигурация зерен в данном объёме породы. Для исследования влияния размера пробы на пористые характеристики использовали осадочные породы карбонского возраста. На данных материалах можно оказательно доказать, каким образом минеральный состав и текстура горной породы могут оказать влияние на результаты порометрических измерений (типичные примеры приводятся на рис. 1–4).

Составной частью работы является предложение методической инструкции для отбора и обработки проб и оценка результатов порометрических измерений. Рекомендуемые минимальные размеры проб, отбираемых основных петрографических типов кластических пород приводятся на рис. А1. Предлагаемая методика оказывается пригодной для всех видов кластических осадочных пород с разной степенью диагенезиса и возраста.

Воспроизводимость установления пористых характеристик осадочных пород исследовали посредством двух наиболее часто применяемых порометров – Porosimeter 2000 с единицей Macropore 120 (Carlo Erba, Италия) и Pore Sizer 9310 (Micromeritics, США). Было доказано, что различный способ заполнения дилатометров у обоих приборов может при рутинерских анализах вызвать многократно высшее различие результатов по сравнению с рассеянием повторяемого измерения.

Однако учитивая приводимое влияние, можно кривые рассеяния проб горных пород, установленные посредством приборов обоих типов весьма незатруднительно объединить только объемной трансляцией (рис. 5, 6).

Рис. 1. Влияние размера пробы на общий объем пор, установленный с помощью ртутной порометрии 1: конгломерат 1B, V_p (100 %) = 24,0 мм³/г, прибор Pore Sizer 9310.

Рис. 2. Влияние размера пробы на общий объем пор, установленный с помощью ртутной порометрии II: песчаник со средним размером зерна 3A, V_p (100 %) = 35,5 мм³/г, Pore Sizer 9310, Porosimeter 2000 и Macropore 120.

Рис. 3. Диаграмма распределения объемов пор в категориях A–B–C, конгломерат 1B, Pore Sizer 9310, A – доля объема пор параметром $r > 0,5$ μм на общий объем пор пробы V_p (100%), B – доля объема пор параметром $r = 0,05 – 0,5$ μм на общий объем пор пробы V_p (%), C – доля объема пор параметром $r < 0,05$ μм на общий объем пор пробы V_p (%); стрелка изображает направление понижения размера осколков.

Рис. 4. Диаграмма распределения объема пор в категориях α–β–γ, песчаник со средним размером зерна 3A, α – доля объема пор параметром $r > 4$ μм на общий объем пор пробы V_p (%), β – доля объема пор параметром $r = 0,1 – 4$ μм на общий объем пор пробы V_p (%), γ – доля объема пор параметром $r < 0,1$ μм на общий объем пор пробы V_p (%); стрелка изображает направление понижения размера осколка, 1 – Pore Sizer 9310, 2 – Porosimeter 2000 с единицей Macropore 120.

Рис. 5. Кумулятивная кривая распределения пор, песчаник со средним размером зерна 3B, 1 – Pore Sizer 9310, 2 – Porosimeter 2000 с единицей Macropore 120, 3 – кривая, перенесенная на уровень кривой (1), вертикальное смещение на 2,3 мм³/г.

Рис. 6. Кумулативная кривая распределения пор, песчаник со средним параметром зерна 3A, 1 –Pore Sizer 9310, 2 – Porosimeter 2000 с единицей Macropore 120, 3 – кривая (2), перенесенная на уровень кривой (1), вертикальное смещение на 1,4 мм³/г.

Рис. A1. Минимальные размеры проб, предназначенных для ртутной порометрии кластических осадочных пород: d – рекомендуемый минимальный размер проб, M_d – средний размер кластических зерен, A – конгломераты, B – крупнозернистый песчаник, C – среднезернистый песчаник, D – мелкозернистый песчаник, E – крупнозернистый алеврит, F – мелкозернистый алеврит, G – аргиллиты.